Interaction between osseous and non-osseous vibratory stimulation of the human cadaveric head

Sim, J H ; Dobrev, I ; Gerig, R ; Pfiffner, F ; Stenfelt, S ; Huber, A M ; Röösli, C

Abstract: Bone conduction (BC) stimulation can be applied by vibration to the bony or skin covered skull (osseous BC), or on soft tissue such as the neck (non-osseous BC). The interaction between osseous and non-osseous bone conduction pathways is assessed in this study. The relation between bone vibrations measured at the cochlear promontory and the intracranial sound pressure for stimulation directly on the dura and for stimulation at the mastoid between 0.2 and 10 kHz was compared. First, for stimulation on the dura, varying the static coupling force of the BC transducer on the dura had only a small effect on promontory vibration. Second, the presence or absence of intracranial fluid did not affect promontory vibration for stimulation on the dura. Third, stimulation on the mastoid elicited both promontory vibration and intracranial sound pressure. Stimulation on the dura caused intracranial sound pressure to a similar extent above 0.5 kHz compared to stimulation on the mastoid, while promontory vibration was less by 20-40 dB. From these findings, we conclude that intracranial sound pressure (non-osseous BC) only marginally affects bone vibrations measured on the promontory (osseous BC), whereas skull vibrations affect intracranial sound pressure.

DOI: https://doi.org/10.1016/j.heares.2016.01.013

Interaction between osseous and non-osseous vibratory stimulation

Sim JH[1,2], Dobrev I[1,2], Gerig R[1,2], Pfiffner F[1,2], Stenfelt S[3], Huber AM[1,2] and Röösli C[1,2]

[1] Department of Otolaryngology, Head and Neck Surgery, University Hospital Zürich, Switzerland

[2] University of Zurich, Switzerland

[3] Department of Clinical and Experimental Medicine, Linköping University, Linköping, Sweden.

HIGHLIGHTS:

- Promontory vibration (osseous bone conduction) and intracranial sound pressure (non-osseous bone conduction) were measured in human cadaveric whole heads in response to bone-conducted sound.
- A bone conduction stimulator was attached either to the mastoid and placed on the dura without contacting surrounding bone.
- Intracranial sound pressure was comparable > 500 Hz for both modes of stimulation.
- Promontory vibration was less by 20-40 dB for stimulation on the dura.
- Dura stimulation only marginally affects bone vibrations as measured on the promontory, whereas stimulation on the mastoid affects intracranial sound pressure.

ABSTRACT

A vibratory stimulation such as bone conduction (BC) stimulus can be applied by stimulation on the bony skull, on the skin covered skull (osseous BC), or by stimulating soft tissue, i.e. neck (non-osseous BC). The interaction between osseous and non-osseous BC pathways is assessed in this study. The relation between bone vibrations measured at the cochlear promontory and the intracranial sound pressure for stimulation directly on the dura and for stimulation at the mastoid between 0.2 – 10 kHz was compared. First, for stimulation on the dura, varying the static coupling force of the BC transducer on the dura only had a small effect on promontory vibration. Second, the presence or absence of intracranial fluid did not affect promontory vibration for stimulation on the dura. Third, stimulation on the mastoid elicited both promontory vibration and intracranial sound pressure. Stimulation on the dura caused intracranial sound pressure to a similar extent above 0.5 kHz compared to stimulation on the mastoid, while promontory vibration was less by 20-40 dB. From these findings, we conclude that intracranial sound pressure (non-osseous BC) affects bone vibrations measured on the promontory (osseous BC) only marginally, whereas skull vibrations affect intracranial sound pressure.

KEY WORDS: Bone conduction, intracranial sound pressure, promontory vibration, dura stimulation.

ABBREVIATIONS: AC, air conduction; BC, bone conduction; MRI, magnetic resonance imaging; BERA, brainstem evoked response audiometry; LDV, laser Doppler vibrometry; SNR, signal-to-noise ratio.

1. INTRODUCTION

A hearing sensation can be elicited when a stimulus is presented not only by air conduction but also by bone conduction (BC), or by a combination of the two. Several different pathways and their interactions have been demonstrated to contribute to BC hearing (Stenfelt, 2006; Stenfelt et al., 2005; Tonndorf, 1966). The importance of these pathways depends on frequency and the state of the middle ear ossicles (Stenfelt, 2014). There are osseous and non-osseous pathways that contribute to the final sensation of hearing. Four osseous BC pathways have been identified, and include: a) pathways involving bone vibration (compression and expansion of the otic capsule (Stenfelt, 2014; Tonndorf, 1966; von Bekesy, 1960); b) sound radiated in the external auditory canal (Brummund et al., 2014; Stenfelt et al., 2003); c) inertia of the ossicles (Homma et al., 2010; Stenfelt, 2006; Stenfelt et al., 2002);d) inertia of the inner ear fluid (Kim et al., 2011; Stenfelt, 2014). One non-osseous BC pathway has been documented (Sohmer et al., 2004). The non-osseous pathway may involve a possible mechanism that includes dynamic sound pressure transmission from the contents of the skull such as brain tissue and cerebrospinal fluid via the internal auditory canal, cochlear aqueduct and/or vestibular aqueduct to the cochlea. Evidence for the non-osseous mechanism has come from studies both on experimental animals (Sohmer et al., 2004) and humans (Sohmer et al., 2000).

In order to induce a hearing sensation, a BC transducer can be placed at various locations on the body. Besides stimulating on the skull or skin covered bone, stimulation on soft tissue (soft-tissue stimulation) such as the eye, neck or thorax can cause a hearing sensation. For example, distorsion product otoacoustic emissions can be elicited by a combination of an air conducted stimulus using an earphone in the ear canal and a stimulus on the eye delivered via a BC transducer (Watanabe et al., 2008). Further, soft-tissue stimulation is an additional pathway of sound transmission in a high-energy sound field besides air conduction and bone vibration. For example, during an explosion, eliminating air conduction with earplugs and earmuffs offers only limited protection against damage to the ear. With earplugs and earmuffs, protection is limited to 38-43 dB from 1 - 1.4 kHz (Ravicz et al., 2000), or it may be frequency dependent, ranging from 40 to 60 dB (Reinfeldt et al., 2007).

It has been proposed that soft-tissue stimulation by a BC transducer induces an auditory response via a predominantly non-osseous pathway (Adelman et al., 2015;

Freeman et al., 2000; Sohmer et al., 2000). Evidence for this assumption comes from experimental studies using clicks as a stimulus. While brainstem evoked response audiometry (BERA) was recorded, no acceleration of the bone was measured for stimulation of the eye in human (Sohmer et al., 2000) or for stimulation of the brain in experimental animals (Freeman et al., 2000). In amphibians, similar mechanisms have been described, but concurrent bone vibrations could not be ruled out completely although unlikely (Seaman, 2002). In contrast, skull vibrations, as measured on the teeth following stimulation on the eye have been described (Ito et al., 2011) on normally hearing human subjects. While vibration of the teeth was clearly measureable, no direct correlation between the BC threshold and vibration of the teeth was found, suggesting that non-osseous pathways contribute to hearing for this mode of stimulation. One caveat is that vibration of the teeth may not directly correspond to the vibrations of the bone surrounding the cochlea.

Osseous pathways can be investigated by measuring bone vibrations at the cochlear promontory (Eeg-Olofsson et al., 2013), and non-osseous pathways can be assessed by measuring intracranial sound pressure in the head. The aim of this study was to investigate the interaction between non-osseous and osseous pathways following stimulation with a BC transducer by comparing the relation between bone vibrations measured at the cochlear promontory and intracranial sound pressure for stimulation on the dura and on the mastoid (Figure 1). We hypothesized that intracranial sound pressure and skull vibrations would be correlated for the two stimulation modalities depending on stimulation frequency and the presence or absence of cranial fluid in the cadaver heads.

2. METRIALS AND METHODS

2.1 Preparation of specimen

The experiments were reviewed and approved by the institutional Ethics Committee (KEK-ZH-Nr. 2012-0136). Measurements were made on four cadaveric whole human heads that were conserved using a technique described by Thiel (Thiel, 1992).This method does not significantly change the properties of the soft tissue (Guignard et al., 2013). An endaural incision was performed between the helix and the tragus to achieve access to the promontory. Then, the tympanomeatal flap was elevated to expose the middle ear to get direct access to the promontory (Fisch et al., 2008). Two self-retaining retractors were placed to allow good visualization of the promontory and access for the Laser Doppler Vibrometry (LDV) beam, which was used to measure promontory vibrations. To enhance reflectivity of the laser beam, a small piece of retro-reflective foil (i.e., < 1 mm^2) was placed onto the cochlear promontory near the round window on the measurement position. A grove was drilled in the mastoid bone for placement of the BC transducer (*Bonebridge, Med-El, Austria*) just posterior to the wall of the external auditory canal and inferior to the dura of the middle cranial fossa with the dura remaining covered by bone. The BC transducer was secured in its position in the cortical bone with two self-tapping screws of 2 mm diameter and 6 mm length. The attachment of the screws was controlled by tightening them to 0.2 Nm using a torque wrench. A craniotomy (2x2 cm) above the frontal sinus was then made and in a second step, the same BC transducer, which was also used for mastoid stimulation, was pressed against the dura with a controlled coupling force and a contact area with the dura of approximately of 2 cm^2. The coupling force was varied from 1 to 5 Newton via an elastic band in 1 Newton steps, controlled with a spring force gauge (*Light Line, Pesola, Switzerland*). The effect of increasing coupling force on intracranial sound pressure and bone vibration was analyzed. Care was taken to assure that the BC transducer was in contact only with the dura and not with the skull. The skull was opened at the vertex and a tube of 10-mm diameter was tightly sealed to the opening in order to keep a physiologic intracranial static pressure of 15 cm water column.

2.2 Measurement setup

The measurement setup, shown in Figure 2, consisted of an LDV system, hydrophone, and a BC transducer coupled to the cadaveric head at either the mastoid (MastStim) or the dura (DuraStim). For both positions, the BC transducer was directly driven by stepped-sine signals in the frequency range of 0.2 – 6 kHz with a stimulus intensity of 1 V peak, which was generated by the measurement system Audio Precision APx585 (*Audio Precision Inc., USA)*. The 81 stimulus frequencies used were equally spaced on a logarithmic scale, resulting in approximately 50 frequency points per decade. Measurements were performed on a stainless steel table to minimize random vibrations from external sources. A hydrophone (*Type 8103, Brüel & Kjær, Denmark*), used for measurements of the sound-induced pressure variations in the intracranial fluid, was inserted into the intracranial space through the tube. The hydrophone was carefully positioned at the center of the cranial hemisphere such that it did not have contact with the skull, and its position was monitored by an x-ray in two perpendicular planes (Figure 2c). A physiologic static intracranial pressure of 15 cm H_2O was maintained by a water column in the tube attached to the skull (Steiner et al., 2006).

Following stimulation, motions of the cochlear promontory were measured at a single point using an 1-dimentional LDV system (*CLV-2534*, *Polytec GmbH, Germany*). Simultaneously, intracranial sound pressure was measured using the hydrophone with a charge amplifier (Type 2635, Brüel & Kjær, Denmark). Both signals, as well as the driving signal to the BC transducer, were recorded by the Audio Precision APx585 measurement system (Figure 2).

In order to provide sufficient temporal resolution for resolving frequency, magnitude and phase (not shown but recorded for future research) in the desired measurement frequency range (0.2-6 kHz), the maximum sampling rate of the available equipment was used without any compromise on the other sampling parameters (sampling time, input range, noise floor, etc.). The sampling frequency was set at 192 kHz with a sampling time of 200 ms per frequency, resulting in a 5-Hz frequency resolution per measurement. All of the measurement procedures were controlled by the Audio Precision software APx500 (*Audio Precision Inc., USA*) and custom LabView Virtual Instrument (VI) software, created in LabView 2013 SP1 (*National Instruments, Texas, USA*) and installed on a personal computer.

2.3 Data processing and analysis

In order to improve the signal-to-noise ratio (SNR), especially due to the relatively low promontory response for dura stimulation (DuraStim) seen in the results section, each frequency measurement was filtered with a bandpass filter adjusted to each corresponding measurement frequency. Based on pilot tests, a standard band-pass filter with 3rd order Butterworth topology was used, characterized by a 1 dB allowable ripple within the passband, 60 dB attenuation within the stopband, and a 1/6th octave window width, centered relative to each stimulus frequency.

In order to reduce effects from random external disturbances, such as LDV signal drop, each measurement was repeated 5 times and the mean of the data was taken for further analysis.

Initial post-processing was done in the custom LabView VI program, while final post-processing, analysis and representation was done via a custom MATLAB script (*MATLAB 2014a, MathWorks, MA, USA*). Results with an SNR of 10 dB or better were considered for the discussions. The magnitude ratios between intracranial sound pressure and promontory motion for stimulation on the mastoid and for stimulation on the dura were calculated and compared.

3. RESULTS

Intracranial sound pressure and cochlear promontory motion were measurable with an SNR of >10dB for all frequencies for stimulation with the BC transducer fixed to the mastoid. For direct stimulation on the dura, an SNR > 10 dB was obtained in the frequency range of 0.2-5kHz, with the exception of 0.5-0.7 kHz range, which were noted as dotted lines in all relevant figures.

3.1. Effects of varying the experimental conditions

3.1.1. Promontory vibration and intracranial sound pressure for stimulation on mastoid

Promontory vibration for stimulation on the mastoid (MastStim) was comparable among all four specimens across the measured frequency range. The variation remained within 5 dB, indicating that the attachment of the device and the location of stimulation was uniform (Figure 3). Greater variability was observed for intracranial sound pressure, which was around 10 dB across the measured frequency range. The increased variability in intracranial sound pressure may be attributed to variation in the position of the hydrophone, and/or to differences of the material properties of the intracranial content.

3.1.2. Increasing coupling force for stimulation on dura

Effects of altering the coupling force of the BC stimulator on the dura (DuraStim) were analyzed in two heads (Figure 4). Generally, little effect was observed on promontory vibration for varying the coupling force. In head CH4 14-9, the resonance frequency of promontory vibration at around 0.4 – 0.5 kHz shifted to higher frequencies with increased coupling force. No effect in the other frequencies was seen especially not on the highest peak around 1.5 kHz, and no clear trend was seen in head CH6 8-10. Intracranial sound pressure tended to have its highest peak between 1 – 2 kHz in both heads following an increase in coupling force. Head CH4 14-09 shows an increased prepressure that goes along with an increased pressure below 0.5 kHz. An increase in intracranial sound pressure for increased coupling force indicates a rigid coupling of the BC stimulator to the dura. However, the higher coupling force did only lead to an increase in bone vibration in one head between 0.4 – 0.5 kHz, indicating that the interaction between intracranial sound pressure and bone vibration is minimal.

3.1.3. Influence of intracranial fluid on promontory motion for stimulation on dura

To assess the effect of intracranial fluid on bone vibration, stimulation on the dura (DuraStim) was compared in two heads under two conditions. In the first, the heads were fluid filled and an intracranial sound pressure of 15 cm water column was maintained while the coupling force was set at 5 Newton. In the second, the fluid was removed from the skull by passively letting the fluid flowing out of the head (drained head), however the brain tissue was retained. The amount of remaining tissue or fluid was not controlled objectively. Intracranial sound pressure and promontory vibration were compared for the two conditions. Intracranial sound pressure was greater for the fluid filled condition. The differences between the two heads may be explained by differences in the amount of remaining water. Promontory vibration only showed an increase in magnitude around 0.3 kHz and 1.5 kHz, whereas differences were small at the other frequencies (Figure 5).

3.2. Comparison of stimulation on mastoid versus on dura

The magnitude of promontory vibration was larger by 10 to 40 dB for stimulation on the mastoid (MastStim) as compared to stimulation on the dura (DuraStim) (Figure 6). Differences were smallest (i.e., 10 dB) for the low frequencies and increased above 0.5 kHz. Intracranial sound pressure was larger (i.e., 20 dB) for stimulation on the dura (DuraStim) between 0.2 and 0.5 kHz while the differences were smaller (i.e., <10 dB) above 0.5 kHz. Stimulation on the dura (DuraStim) produced the largest values of promontory vibration and intracranial sound pressure between 1.5 – 2 kHz. Similar findings were observed for mastoid stimulation (MastStim); however, the increase in the response was from 0.7-1 kHz. The magnitude ratios defined as intracranial sound pressure over promontory motion (Figure 6, column 3), were considerably larger for stimulation on the dura (DuraStim) compared to stimulation on the mastoid (MastStim) over the entire frequency range. This finding indicates that the transfer of vibration from the skull to the intracranial contents is more efficient than vice versa.

4. DISCUSSION

Both osseous (Stenfelt et al., 2005) and non-osseous pathways (Sohmer et al., 2004) are considered to contribute to hearing from a vibratory stimulus coming from a BC transducer as mentioned above. The interaction of these pathways is not fully understood. Osseous pathways were assessed in this study by measuring promontory vibration (Eeg-Olofsson et al., 2013), while non-osseous pathways were measured by recording intracranial sound pressure for two simulation conditions. In the first condition, the BC transducer was screwed to the mastoid; in the second, it was held against the dura by an elastic band. While it was possible to use a comparable location for the BC transducer on the mastoid and similar fixation of the device as described in the method section, more variability occurred in the placement of the BC stimulator on the dura because of several factors. The location of the exposure of the dura may vary slightly, the coupling force may be different, and the position of the BC transducer may differ, although these factors were controlled as carefully as possible. Further, the hydrophone may have been positioned in a slightly different position in the different heads, although the position was checked with x-ray in two planes. These factors may account for the differences in intracranial sound pressure between the heads. Therefore, the results of the different experimental conditions were analyzed for each head separately rather than averaging results for different conditions and comparing the mean.

For stimulation on the skin covered bone, some investigators have found that the coupling force has no effect on hearing thresholds at 2 kHz (Adelman et al., 2013; Toll et al., 2011) or only a marginal (i.e., ~2 dB) effect from 0.25 – 4 kHz (Toll et al., 2011). Others, however, have reported better thresholds when increasing the coupling force, concluding that output force of a BC stimulator depends on coupling (HARRIS et al., 1953; Hodgetts et al., 2006; Ito et al., 2011). A trend of increasing coupling force and increasing intracranial sound pressure was shown in our study for stimulation on the dura whereas promontory vibration remained relatively unaffected. In one experiment a small increase in the resonance frequency of promontory vibration as coupling force of the BC stimulator on the dura was increased was observed around 0.3 - 0.5 kHz, possibly related to changes in the mechanical impedance (Stenfelt and Goode, 2005) of the coupling between the BC transducer, dura and skull. This finding leads to the conclusion that promontory vibration is not significantly affected by intracranial sound pressure.

This is further supported by comparison of promontory vibration and dura stimulation for the two conditions in which the head was fluid filled or drained for stimulation on the mastoid (MastStim). First of all, the amount of remaining tissue and/or fluid was not objectively controlled. Therefore, the differences of draining the head between the two heads may be explained by this fact. For example, the resonances at between 1-2 kHz is only affected in head CH6 8-10, or intracranial pressure is only affected below 1 kHz in head CH 14 14-9. Overall, there was only a marginal effect of the presence of intracranial fluid on the promontory vibration. This suggests that the sound transmission between the BC transducer and the promontory is most likely a local effect at the site of stimulation and not influenced by the presence of intracranial fluid. This finding indicates that investigations on bone vibration in response of vibratory stimulation can be performed on drained heads. The measurements of intracranial sound pressure in the drained heads need to be interpreted with great caution, because the hydrophone is designed to measure pressure in fluid. When fluid is absent, the accuracy of measurements of the hydrophone, which is placed in more viscous brain tissue, may lack accuracy.

Promontory motion and intracranial sound pressure changes are measurable with an SNR > 10dB, with the BC transducer attached to the mastoid (MastStim) and to the dura (DuraStim). Promontory vibrations with stimulation on the dura (DuraStim) were 10-40 dB smaller at all frequencies than promontory vibrations with stimulation on the mastoid (MastStim), and the difference increased with frequency. This is consistent with previous measurements (Stenfelt and Goode, 2005) of promontory vibration with bone stimulation at the skull's vertex versus at the mastoid. Intracranial sound pressure was comparable for both stimulation methods above 0.5 kHz. This suggests that the coupling between the BC transducer and the skull, for stimulation on the dura (DuraStim), through the band is not significant for frequencies above 0.5 kHz. Further reduction of the possible coupling could be potentially achieved by supporting the BC transducer independently of the head. These findings suggest that sound transfer from bone to intracranial contents is more efficient above 0.5 kHz than vice versa. Therefore, sound transfer from intracranial fluid to bone is not a major pathway to elicit auditory vibrations. The question of whether intracranial sound pressure can evoke a hearing sensation cannot be answered by our measurement setup on cadaver heads. In the literature, findings are contradictory. Chordekar et al. (Chordekar et al., 2013) observed recordings of auditory brainstem response in sand fat rats for

stimulation on soft tissue without recording bone vibrations above the noise level, claiming that bone vibrations are not involved in this mode of stimulation, while auditory brainstem response and bone vibrations were recorded for stimulation on the bone. In contrast, Ito et al. (Ito et al., 2011) were able to measure bone vibration for stimulation on soft tissue (eye) in human. The difference may come from differences between species or from differences of measurement techniques for bone vibrations. While Chordekar et al. used an LDV, Ito et al. used an accelerometer, which may result in differences of sensitivity and SNR. In our measurements, SNR was improved by attaching a retro-reflective foil on the bone and stimulating with supra-threshold sound pressure, while Chordekar et al. stimulated at hearing threshold.

5. Conclusion

Intracranial sound pressure affects bone vibrations measured on the promontory only marginally. This statement is supported by three of our findings: 1) increases in applied contact pressure between the BC transducer and the dura increases intracranial sound pressure but does not affect bone vibration; 2) the presence or absence of intracranial fluid does not significantly affect bone vibration for stimulation on the dura (DuraStim) while the intracranial sound pressure is significantly affected; 3) stimulation on the dura (DuraStim) evoked increases in intracranial sound pressure more than did mastoid stimulation (MastStim) below 0.5 kHz, but only limited promontory vibration. Stimulation on the mastoid (MastStim) evoked intracranial sound pressure as well as promontory vibration for frequencies above 0.5 kHz. Maybe, a hybrid stimulation is beneficial in some situations.

References

Adelman, C., Sohmer, H. 2013. Thresholds to soft tissue conduction stimulation compared to bone conduction stimulation. Audiol Neurootol 18, 31-5.

Adelman, C., Kaufmann Yehezkely, M., Chordekar, S., Sohmer, H. 2015. Relation between Body Structure and Hearing during Soft Tissue Auditory Stimulation. Biomed Res Int 2015, 172026.

Brummund, M.K., Sgard, F., Petit, Y., Laville, F. 2014. Three-dimensional finite element modeling of the human external ear: simulation study of the bone conduction occlusion effect. J Acoust Soc Am 135, 1433-44.

Chordekar, S., Perez, R., Adelman, C., Sohmer, H. 2013. Assessment of inner ear bone vibrations during auditory stimulation by bone conduction and by soft tissue conduction. J Basic Clin Physiol Pharmacol 24, 201-4.

Eeg-Olofsson, M., Stenfelt, S., Taghavi, H., Reinfeldt, S., Håkansson, B., Tengstrand, T., Finizia, C. 2013. Transmission of bone conducted sound - correlation between hearing perception and cochlear vibration. Hear Res 306, 11-20.

Fisch, U., May, J.S., Linder, T. 2008. Tympanoplasty, mastoidectomy and stapes surgery. 2nd ed. Thieme, Stuttgart, New York.

Freeman, S., Sichel, J.Y., Sohmer, H. 2000. Bone conduction experiments in animals - evidence for a non-osseous mechanism. Hear Res 146, 72-80.

Guignard, J., Stieger, C., Kompis, M., Caversaccio, M., Arnold, A. 2013. Bone conduction in Thiel-embalmed cadaver heads. Hear Res 306, 115-22.

HARRIS, J.D., HAINES, H.L., MYERS, C.K. 1953. A helmet-held bone conduction vibrator. Laryngoscope 63, 998-1007.

Hodgetts, W.E., Scollie, S.D., Swain, R. 2006. Effects of applied contact force and volume control setting on output force levels of the BAHA Softband. Int J Audiol 45, 301-8.

Homma, K., Shimizu, Y., Kim, N., Du, Y., Puria, S. 2010. Effects of ear-canal pressurization on middle-ear bone- and air-conduction responses. Hear Res 263, 204-15.

Ito, T., Röösli, C., Kim, C.J., Sim, J.H., Huber, A.M., Probst, R. 2011. Bone conduction thresholds and skull vibration measured on the teeth during stimulation at different sites on the human head. Audiol Neurootol 16, 12-22.

Kim, N., Homma, K., Puria, S. 2011. Inertial bone conduction: symmetric and anti-symmetric components. J Assoc Res Otolaryngol 12, 261-79.

Ravicz, M.E., Melcher, J.R., Kiang, N.Y. 2000. Acoustic noise during functional magnetic resonance imaging. J Acoust Soc Am 108, 1683-96.

Reinfeldt, S., Stenfelt, S., Good, T., Håkansson, B. 2007. Examination of bone-conducted transmission from sound field excitation measured by thresholds, ear-canal sound pressure, and skull vibrations. J Acoust Soc Am 121, 1576-87.

Seaman, R.L. 2002. Non-osseous sound transmission to the inner ear. Hear Res 166, 214-5.

Sohmer, H., Freeman, S. 2004. Further evidence for a fluid pathway during bone conduction auditory stimulation. Hear Res 193, 105-10.

Sohmer, H., Freeman, S., Geal-Dor, M., Adelman, C., Savion, I. 2000. Bone conduction experiments in humans - a fluid pathway from bone to ear. Hear Res 146, 81-8.

Steiner, L.A., Andrews, P.J. 2006. Monitoring the injured brain: ICP and CBF. Br J Anaesth 97, 26-38.

Stenfelt, S. 2006. Middle ear ossicles motion at hearing thresholds with air conduction and bone conduction stimulation. J Acoust Soc Am 119, 2848-58.

Stenfelt, S. 2014. Inner ear contribution to bone conduction hearing in the human. Hear Res 329, 41-51.

Stenfelt, S., Goode, R.L. 2005. Bone-conducted sound: physiological and clinical aspects. Otol Neurotol 26, 1245-61.

Stenfelt, S., Hato, N., Goode, R.L. 2002. Factors contributing to bone conduction: the middle ear. J Acoust Soc Am 111, 947-59.

Stenfelt, S., Wild, T., Hato, N., Goode, R.L. 2003. Factors contributing to bone conduction: the outer ear. J Acoust Soc Am 113, 902-13.

Thiel, W. 1992. [An arterial substance for subsequent injection during the preservation of the whole corpse]. Ann Anat 174, 197-200.

Toll, L.E., Emanuel, D.C., Letowski, T. 2011. Effect of static force on bone conduction hearing thresholds and comfort. Int J Audiol 50, 632-5.

Tonndorf, J. 1966. Bone conduction. Studies in experimental animals. Acta Otolaryngol, Suppl 213:1+.

von Bekesy, G. 1960. Experiments in hearing McGraw-Hill, New York.

Watanabe, T., Bertoli, S., Probst, R. 2008. Transmission pathways of vibratory stimulation as measured by subjective thresholds and distortion-product otoacoustic emissions. Ear Hear 29, 667-73.

Figures

Figure 1

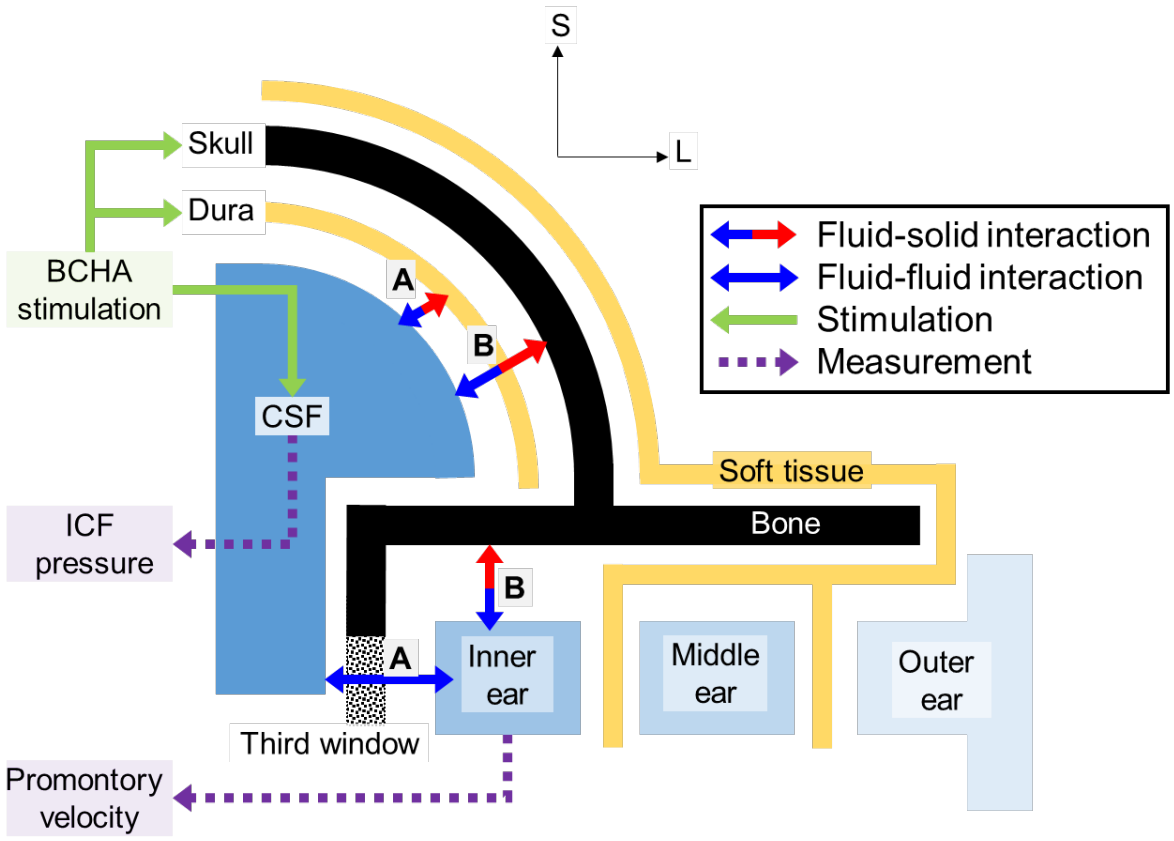

Fig. 1. A simplified scheme of the human head, with corresponding interface boundaries and interaction types among all components. Each stimulation type DuraStim (A) and MastStim (B) provides stimulation to the inner ear via different BC pathways. Indicated are stimulation locations (Dura, Skull) and measured parameters (ICF pressure, Promontory motion) for all experiments.

Figure 2

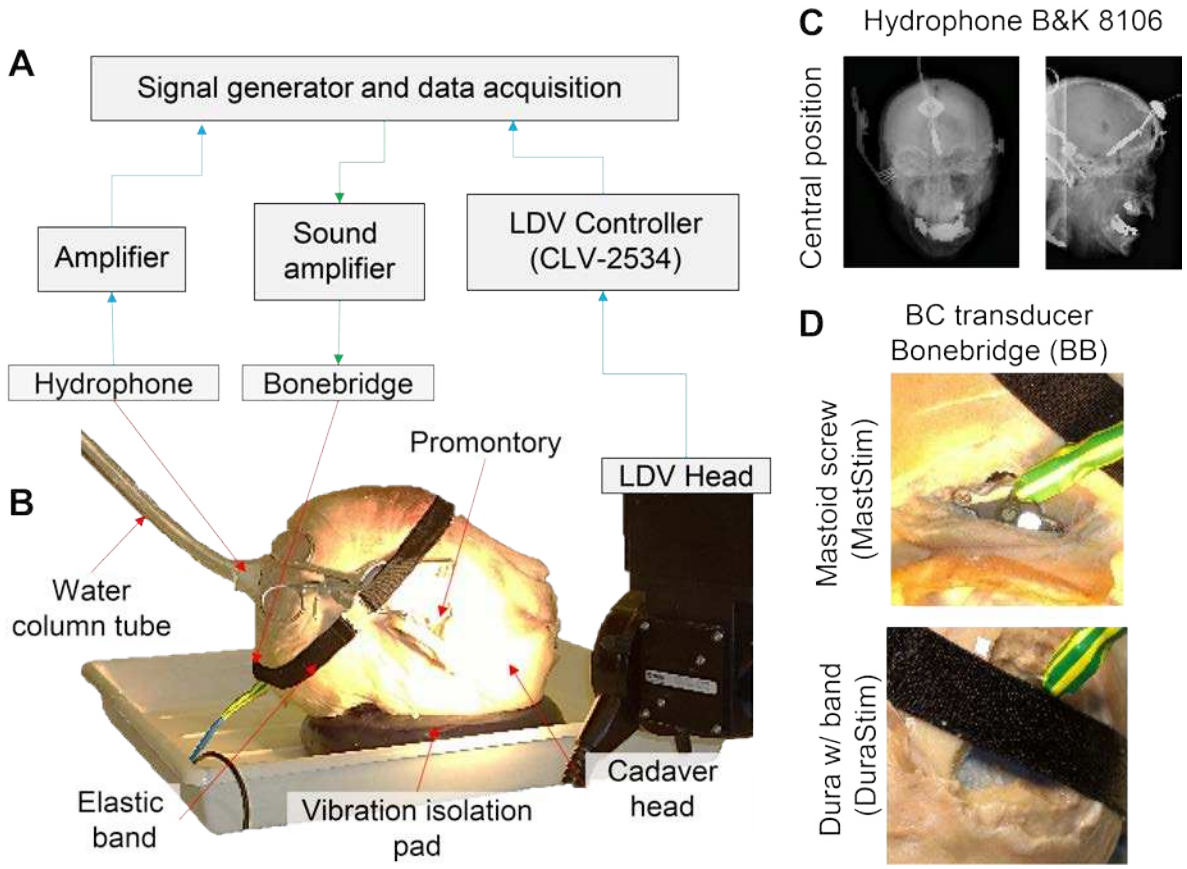

Fig. 2. Overview of the measurement system (A), experimental setup (B), hydrophone (C) and BC transducer (D) location. The measurement system (A) provided a unified user interface for control over the excitation signal generation and the data acquisition. The experimental setup (B) for each measurement included an LDV, measuring the promontory motion, as well as hydrophone in central or temporal position to measure fluid pressure. The excitation was provided via a BC transducer (Bonebridge) (D) attached either to the mastoid (MastStim) with screws, or placed on the dura (DuraStim) with headband.

Figure 3

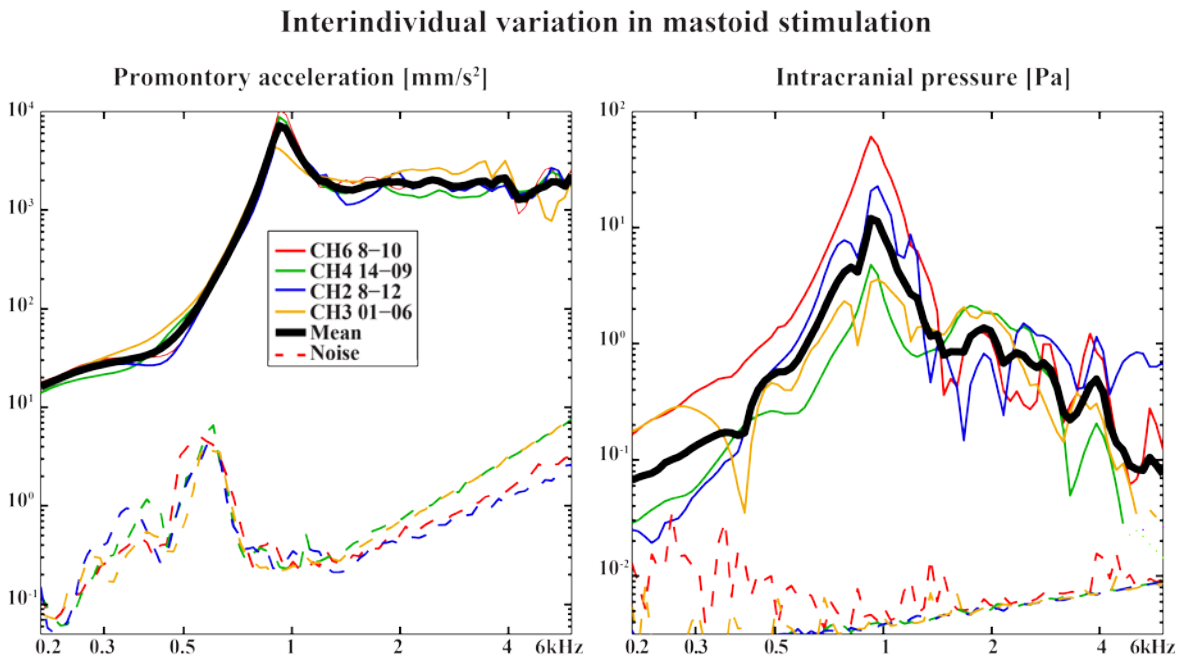

Fig. 3. Variability of promontory motion and intracranial pressure for mastoid stimulation. Promontory motion, due to mastoid stimulation (MastStim), shows small variations (i.e., < 5 dB variation) among all four cadaver heads, while intracranial sound pressure variations are larger (i.e., 10 dB variation). The noise floor for each measurement is noted with a corresponding dotted line. Data with SNR <10 dB are indicated with dotted lines.

Figure 4

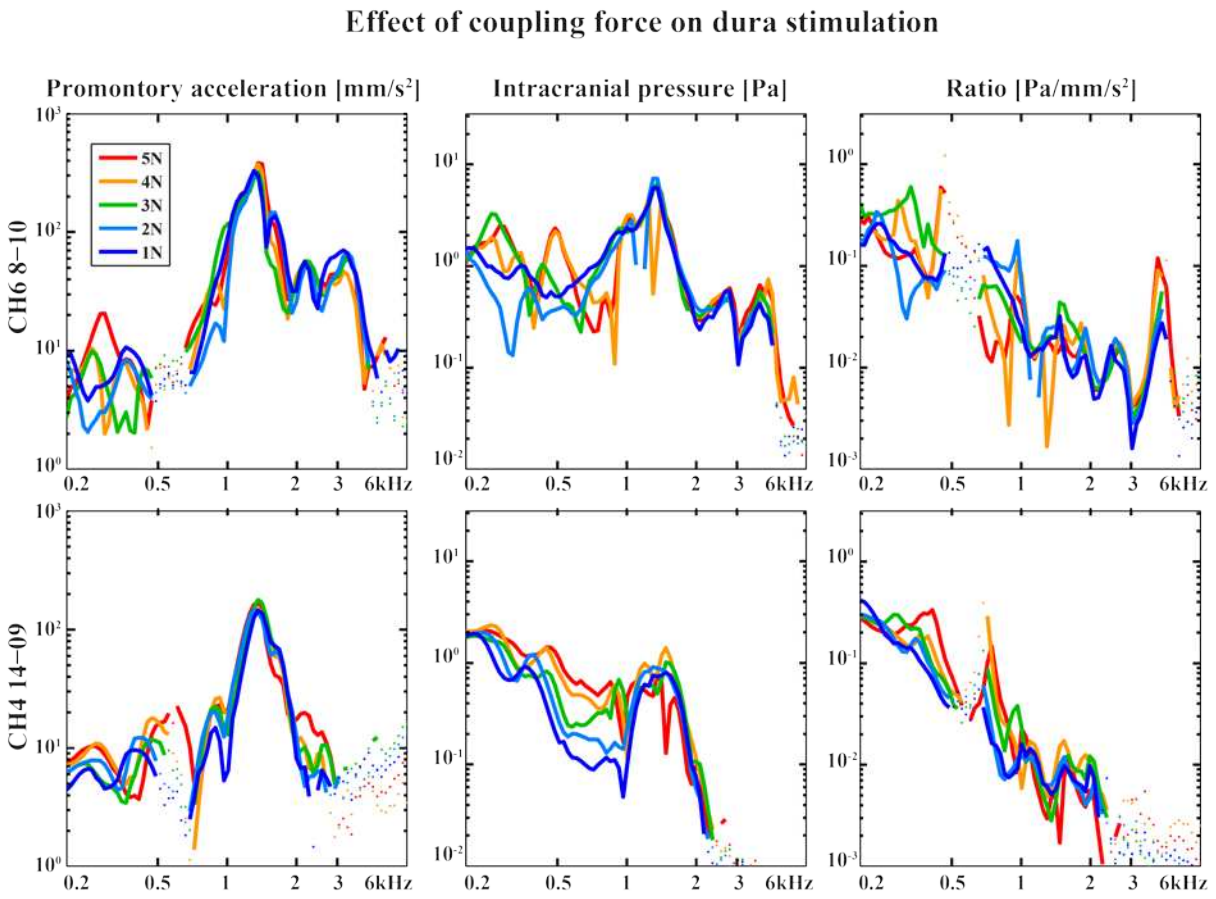

Fig. 4. Promontory acceleration (left), intracranial sound pressure (middle) and their ratio (right) for stimulation on the dura (DuraStim) with different coupling forces from 1 to 5 Newton for two heads. Data with SNR <10 dB are indicated with dotted lines.

Figure 5

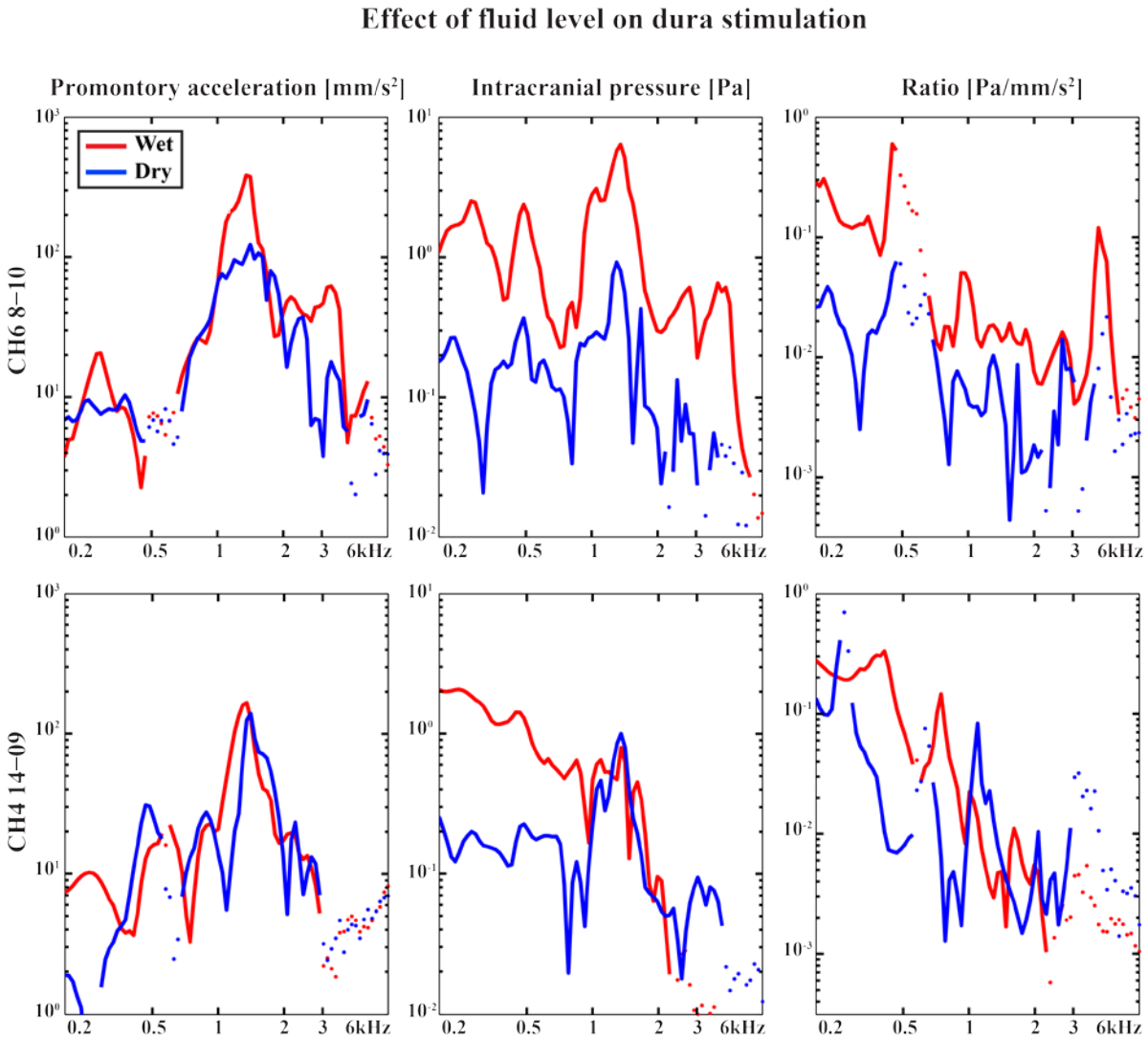

Fig. 5. The effect of fluid level of the intracranial content on promontory acceleration (left), intracranial sound pressure (middle) and their ratio (right) in two cadaver heads. The intracranial fluid level has smaller effect on promontory motion than on intracranial sound pressure. Data with SNR <10 dB are indicated with dotted lines.

Figure 6

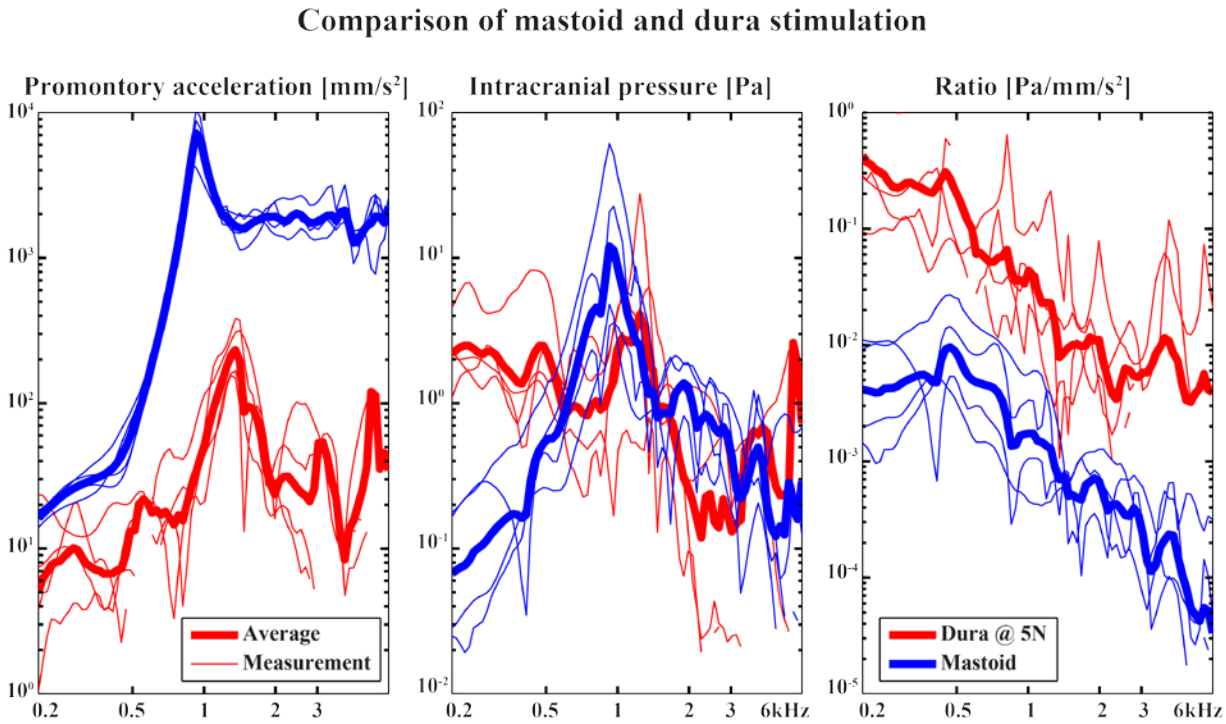

Fig. 6. Promontory acceleration (left), intracranial sound pressure (middle) and their ratio (right) for stimulation of the mastoid (MastStim. blue) and dura (DuraStim, red) for four cadaver heads. Coupling force for dura stimulation (DuraStim) was set at 5 N. Individual data are shown with thin lines, averages with thick lines. Data with SNR <10 dB are omitted.